U.S. DEPARTMENT OF COMMERCE
National Technical Information Service
PB-298 472

Emissions from FBC (Fluidized Bed Combustion Boilers)

(U.S.) Industrial Environmental Research Lab,
Research Triangle Park, NC

1978

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO.	2.	3. REC
EPA-600/J-78-112	JOURNAL ARTICLE	PB 298472

4. TITLE AND SUBTITLE	5. REPORT DATE
Emissions from FBC Boilers, (formerly: Enviromental Emissions from Coal-Fired Industrial Fluidized-Bed Boilers.)	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) D.B. Henschel (IERL-RTP)	8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Same as block 12.	10. PROGRAM ELEMENT NO.
	11. CONTRACT/GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS **EPA, Office of Research and Development Industrial Environmental Research Laboratory Research Triangle Park, NC 27711**	13. TYPE OF REPORT AND PERIOD COVERED Journal publication
	14. SPONSORING AGENCY CODE **EPA/600/13**

15. SUPPLEMENTARY NOTES Printed in Enviromental Science and Technology, Vol. 12, No. 5, 5/78.

16. ABSTRACT The paper provides perspective regarding the enviromental acceptability of atmospheric-pressure fluidized-bed boilers, with particular emphasis on the application of this technology as a technique for utilizing coal in the industrial sector. It reviews emission sources within the process, and applicable Federal environmental regulations. It summarizes available information on emissions and control of SO_2, NO_x, and particulates from atmospheric fluidized-bed combustion units, as well as information on the enviromental characteristics of the solid residue that is produced. It is concluded that atmospheric fluidized-bed boilers should be technically capable of meeting existing New Source Performance Standards for SO_2, NO_x, and (probably) particulate emissions from large coal-fired steam generators. Preliminary data on the solid residue suggest that the residue should not present a disposal problem from the standpoint of certain leachate characteristics, but that further consideration of other leachate characteristics is necessary to ensure that disposal problems do not exist.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Pollution	Pollution control	13B
Boilers	Stationary sources	13A
Fluidized bed processors	Particulate	13I
Coal	Leachate	21D
Combustion		21B
Sulfur Oxides, Nitrogen Oxides		07B
Dust		11G

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS (This Report)	21. NO. OF PAGES
Release to Public	Unclassified	7
	20. SECURITY CLASS (This page) Unclassified	22. PRICE A02-A01

EPA Form 2220-1 (9-73)

REPRODUCED BY NATIONAL TECHNICAL INFORMATION SERVICE U.S. DEPARTMENT OF COMMERCE SPRINGFIELD, VA. 22161

Emissions from FBC boilers

In order that fluidized-bed combustion (FBC) may be in compliance, its air and water effluents must be known. Here is some insight into what they are

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In view of the national objective of achieving energy self-sufficiency in the U.S., there is increasing interest in utilizing this nation's abundant coal resources. Increased use of coal is an important component of the President's energy plan—including increased coal usage in the industrial sector. On the other hand, coal is generally a less attractive fuel than oil or natural gas; it presents a greater potential environmental problem, it is not as easy to handle, and, with historic fuel and combustion equipment costs, it has frequently been more expensive to utilize.

Environmental concerns regarding coal usage have resulted in substantial outlays of funds for the development and installation of environmental control equipment for coal combustion applications. The desire to assure an acceptable environment has, in fact, resulted in some proposed restraints against the use of coal in industrial combustors, a trend in opposition to the objectives of the national energy plan. Therefore, it is in the national interest to assure that adequate alternative technologies are available to enable combustion of coal in an environmentally acceptable *and* economically feasible manner, in the industrial sector and other use sectors.

A promising technology

One of the promising alternative technologies that may accomplish this objective is fluidized-bed combustion. Fluidized-bed combustion is not a new technology. It has been employed commerically in various applications, such as gas- and oil-fired limestone calciners and ore roasters, sludge incinerators, and refinery catalytic cracker regenerators.

However, the application of the technology to efficient coal combustion for heat, steam and power generation is still under development. A variety of experimental studies over the past decade have shown that fluidized-bed coal combustion offers promise as an efficient coal-combustion process with favorable combustion and heat-transfer characteristics. It also provides an effective environment for reducing emissions of sulfur dioxide and nitrogen oxides. Current assessments indicate that utilization of coal-fired fluidized-bed combustion (FBC) in industrial applications is potentially promising.

The primary responsibility within the Federal government for development of fluidized-bed coal-combustion technology lies with the U.S. Energy Research and Development Administration (ERDA), now part of the Department of Energy (DOE). DOE is conducting a variety of programs aimed at the development of alternative variations of the technology, for alternative applications (electric utility, industrial, and residential/commercial applications).

The prime element of the DOE program for industrial application of fluidized-bed coal combustion is the cost-sharing of five industrial units of three types. The three types of industrial applications include

- industrial steam generators producing superheated steam, including a 50 000 lb steam/h (22 700 kg/h) unit by Combustion Engineering
- industrial boilers producing saturated steam, including a 100 000 lb steam/h (45 400 kg/h) boiler at Georgetown University
- a 25 000 lb steam/h (11 300 kg/h) multisolid fluidized-bed combustion unit at Battelle
- indirect fired heaters to heat process streams, including a 10–15 million Btu/h (2 5—3.8 million kcal/h) crude oil heater at Exxon
- a 28 million Btu/h (7.1 million kcal/h) air heater by Fluidyne at Owatonna Tool Co.

Some of these units may come on-stream as early as calender 1979.

In addition to these projects, DOE has started up the 30-MW atmospheric fluidized-bed boiler at Rivesville, W.Va. It is also conducting a variety of other projects which, although not oriented solely toward industrial applications, will provide support to the application of fluidized-bed combustion in the industrial sector.

In addition to the work being conducted by DOE, projects are being sponsored by the Electric Power Research Institute (EPRI). These projects primarily address electric utility applications of FBC, but will generate data of value in the development of industrial boilers. The largest EPRI-sponsored fluidized-bed combustor is a 6-by-6 ft atmospheric unit, which is now being shaken down by Babcock and Wilcox in Alliance, Ohio.

Efforts aimed at industrial applications of fluidized-bed combustion are also being conducted abroad. Babcock and Wilcox, Ltd., in the United Kingdom, has converted a stoker-fired boiler into a 40 000-lb steam/h coal-fired atmospheric

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EPA-600/J-78-112
JOURNAL ARTICLE

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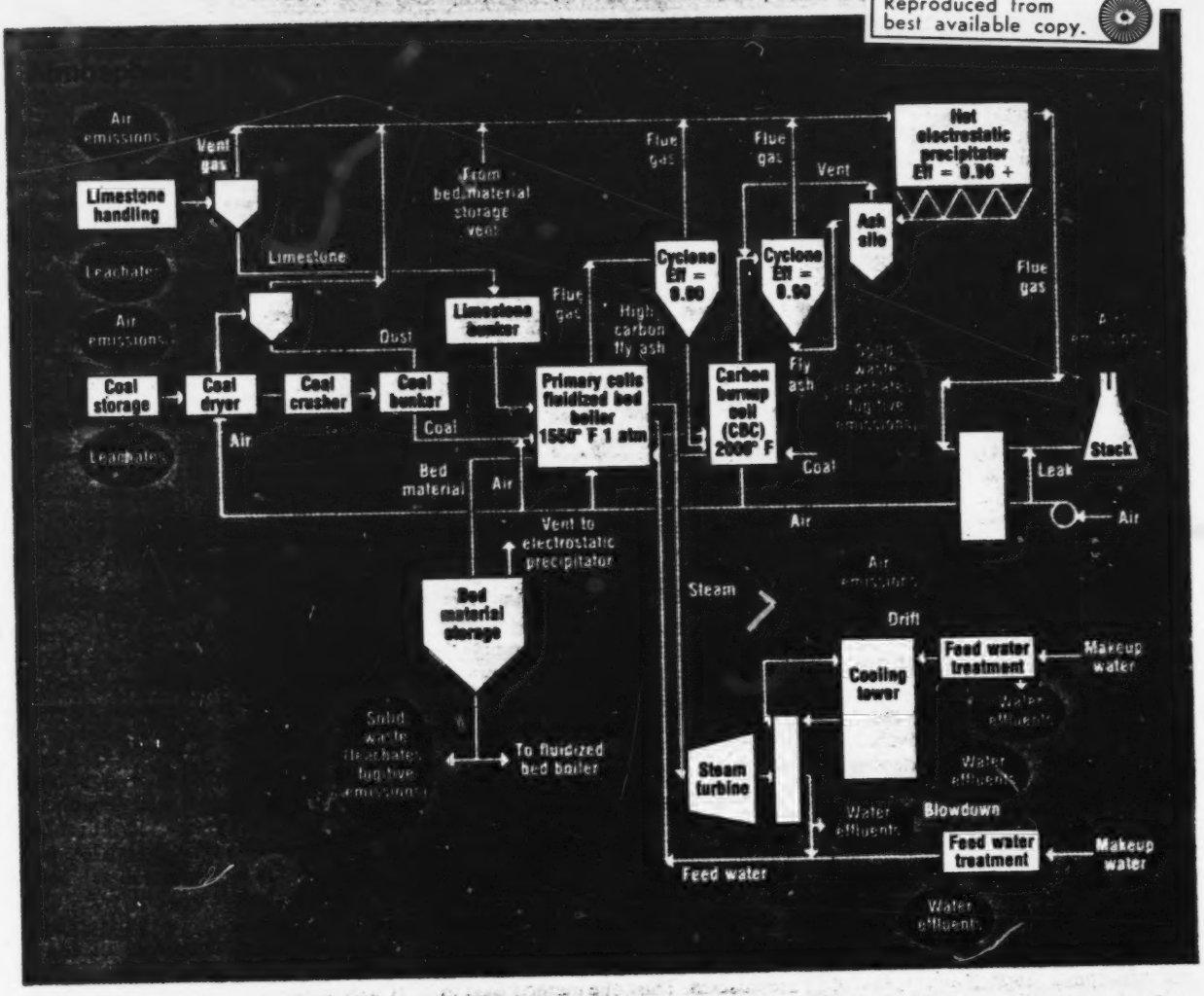


fluidized-bed boiler at Renfrew, Scotland.

In parallel with the efforts to develop fluidized-bed coal-combustion technology, the U.S. Environmental Protection Agency (EPA) is conducting a contract research and development program—currently valued at $4 million annually—aimed at environmental characterization of all variations and all applications of the process. This program has been on-going since 1967.

The objective of the EPA program is to identify potential environmental problem areas, and to develop any necessary environmental control technology, while the fluidized-bed combustion process is still under development. Conducting the environmental characterization concurrent with the combustion technology development should enable any necessary environmental controls to be integrated into the process on the most timely and cost-effective basis. The primary function of EPA's R&D program is to assure the availability of an adequate research data base, and adequate control technology, and to support the development of standards and guidelines by EPA's regulatory offices. It is expected that first-generation industrial FBC will have atmospheric-pressure combustors.

Emission sources

Four general sources of emissions are apparent in Figure 1, adapted from the initial Rivesville boiler design:

- storage and handling of coal and limestone prior to feeding. Emissions can arise from open solids storage piles (e.g., fugitive emissions of wind-blown dust, leaching from rainwater) and from such handling steps as coal drying and crushing. In the Rivesville design, efforts have been made to prevent the dust from these operations from being emitted to the environment
- the steam cycle. Emissions include drift from any cooling tower, and liquid effluents from boiler blowdown and feedwater treatment
- stack gas emissions
- solid residue emissions, in the form of spent limestone-bed material withdrawn from the combustor, and in the form of carryover (largely fly ash, with some elutriated spent sorbent) that is removed from the flue gas by the particle control devices.

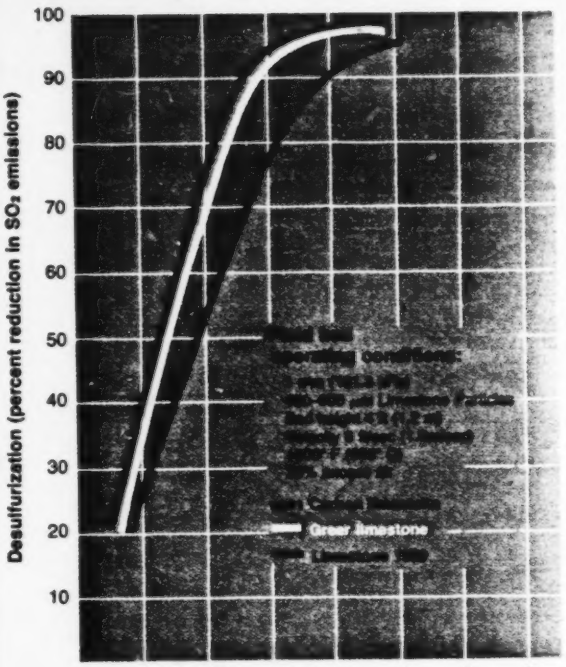
Applicable federal standards

Three types of Federal EPA standards apply to air pollutants, in accordance with the Clean Air Act of 1970, as amended:

- new source performance standards (NSPS), which specify acceptable emission concentrations from new or substantially modified sources and are based upon best available control technology
- ambient air quality standards (AAQS), which specify acceptable concentrations in the atmosphere and are based on health/ecological effects
- hazardous air pollutant emission standards, pertaining to pollutants that are such hazards that no AAQS would be applicable.

FIGURE 2

Projected desulfurization performance of atmospheric fluidized-bed coal combustor, based upon model developed by Westinghouse.



Currently, there are no NSPS for steam generators smaller than 250 million Btu/h heat input. Many industrial boilers are smaller than that limit, and hence are not covered. The proposal by EPA of NSPS for boilers smaller than 250 million Btu/h is probably at least a year away.

Under the Clean Air Act, each state is responsible for providing an implementation plan describing how the AAQS will be implemented, maintained and enforced within each air quality-control region within that state. Environmental restrictions on coal-fired fluidized-bed boilers may result through this mechanism, in addition to restrictions resulting from any pertinent NSPS. AAQS have been promulgated for SO_2, NO_2, particulates, CO, non-methane hydrocarbons and photochemical oxidants.

The framework for establishing environmental standards for solid residue disposal is defined in the Resource Conservation and Recovery Act of 1976. However, such standards for solid residue from coal-fired boilers have not yet been promulgated. This Act requires EPA to promulgate, by April, criteria for ascertaining whether a solid waste is considered "hazardous," and to promulgate standards covering generation of hazardous wastes. These standards must specify recordkeeping, labeling and reporting practices, and will cover facilities that contain, treat, store and dispose of such wastes.

The Act also requires EPA to establish guidelines for the states to prepare solid waste management plans. These state plans must specify the methods that will be used to dispose of all solid wastes in a manner that is environmentally sound, and conserves resources.

It is not known at this time if FBC residue will be considered "hazardous", and thus subject to federal, as well as any state restrictions. If found *not* to be "hazardous", the residue would be subject only to restrictions developed by the individual states under their respective management plans. Disposal of solid waste by ocean dumping, and disposal to mines, are covered by other Federal statutes.

SO_2 emissions

Data available to date suggest that atmospheric fluidized-bed combustors should be able to meet the current NSPS for large coal-fired steam generators, even with fairly high-sulfur coals, if adequate quantities of sorbent are injected. Thus, the method used to control SO_2 emissions from fluidized-bed combustors involves the use of an appropriate sorbent, usually limestone (predominantly calcium carbonate), or perhaps dolomite (containing both calcium and magnesium carbonates).

The fluidized-bed combustor would be operated with the sorbent as the non-combustible bed material. Fresh sorbent would be added continuously, along with the coal, in order to maintain the capture activity of the sorbent bed. Spent sorbent would be drained from the bed as necessary to maintain the bed height.

A typical graph showing projected sulfur removal as a function of fresh sorbent addition rate to an atmospheric fluidized-bed combustor is shown in Figure 2. Figure 2 was generated through use of a kinetics model developed by Westinghouse, and based upon laboratory thermogravimetric analysis data. It was confirmed through use of data from experimental combustors. The sorbent addition rate is expressed in terms of the moles of calcium in the limestone feed divided by the moles of sulfur in the coal (Ca/S molar ratio). Several curves are shown in the figure. The center curve is for Greer limestone (Morgantown, W.Va.), a sorbent that is used at Rivesville. The upper curve for Carbon limestone (Lowellville, Ohio), and the lower curve for Grove limestone (Stephens City, Va.), represent one of the more reactive limestones tested, and one of the less reactive limestones, respectively.

Studies have indicated that the effectiveness of a sorbent in removing SO_2 depends upon a number of combustor variables. In addition to the Ca/S molar ratio, the effectiveness depends heavily upon gas-residence time in the bed, as determined by gas velocity and bed depth and upon sorbent particle size. Other significant variables include sorbent type, as indicated by the curves in Figure 2, and bed temperature.

Figure 2 was generated by assuming a gas velocity of 6 ft/s, a bed depth of 4 ft, a sorbent particle size of 420–500 μ, and a bed temperature of 1500 °F. These conditions are felt to be reasonably typical of what might be ex-

pected in an atmospheric fluidized-bed combustor designed for cost-effective SO_2 control. Design of a combustor for operation at different conditions could, of course, result in performance different from that indicated in Figure 2.

It is useful to express the information in Figure 2 in terms of the quantity of sorbent with which a combustor operator will be dealing. Table 1 shows the amount of sorbent required, based upon the curve for Greer limestone in Figure 2, to meet the current NSPS for large steam generators, as a function of coal sulfur content. The table also indicates the quantity of solid residue that will result.

As a final point, it is emphasized that the data which have been used to develop and verify the model represented by Figure 2, have been generated on relatively small-scale experimental equipment. The largest atmospheric fluidized-bed boiler that has provided substantial SO_2 control data has been a Pope, Evans and Robbins 500-lb coal/h or 5000-lb steam/h Fluidized-Bed Module (FBM) at Alexandria, Va. Substantial SO_2 control data from the Renfrew, Scotland, boiler are not yet available, and the Rivesville and Alliance units are just starting up.

Although sorbent performance in large boilers is not expected to differ drastically from the performance that would be predicted based on the small-scale data and the Westinghouse model, there may be some features of the larger units that could influence performance in a manner not apparent from the small-scale results. Reduced wall effects on the fluidization; different coal distribution patterns within the bed owing to coal feeding technique; and the long-term buildup of fines in the bed, owing to recycle, are several possible factors that might influence sorbent performance in large units.

NO_x emissions

Emissions of nitrogen oxides from atmospheric fluidized-bed combustors generally tend to be below the NSPS for large coal-fired steam generators. The bulk of the emission data, expressed as NO_2, within the typical expected operating temperature range for the primary combustion cells—1500–1600 °F—lie between 0.3–0.6 lb $NO_x/10^6$ Btu. This emission is less than the current emission standard of 0.7 lb/10^6 Btu. Most NO_x emissions that exceeded the current standard were obtained at bed temperatures representative of those expected in the carbon burnup cell—2000 °F and above. Emissions from the burnup cell must be further explored experimentally.

Emissions of NO_x are generally above the level that would be predicted from thermodynamic equilibrium considerations, based upon the reaction of atmospheric nitrogen and oxygen. One explanation for this fact is that most of the NO_x observed from fluidized-bed combustors results not from fixation of atmospheric nitrogen and oxygen, but from oxidation of organic nitrogen compounds in the coal. At primary cell-bed temperatures, probably 80–90% of the NO_x results from fuel nitrogen. NO_x emission levels are well below those that would result if all fuel nitrogen appeared as NO_x in the flue gas. This indicates either that some fuel nitrogen is not converted, or that much of the resulting NO_x decomposes in the bed.

Emissions of NO_x from fluidized-bed combustors have been found to increase to some extent with increasing temperature and increasing excess air, even though oxidation of fuel-bound nitrogen would be expected to be relatively insensitive to temperature in the temperature range of concern. Regression analysis also indicates a decrease in emissions with increasing gas-residence time in the bed. This results from increased time for NO_x decomposition to equilibrium levels, and increased contact time between NO_x and possible reductants, such as carbon and carbon monoxide, in the bed and freeboard. It has also been reported that emissions may be reduced by burning a coal with a lower nitrogen content. As in the case of SO_2 emissions, it is felt that the NO_x emissions should be confirmed by obtaining data on large fluidized-bed combustion units.

Particulates

The ability of atmospheric fluidized-bed combustors to meet the current particulate NSPS for large coal-fired steam generators (0.1 lb/10^6 Btu) has not yet been demonstrated. However, from a practical standpoint, it may be anticipated that control of particulates from fluidized-bed combustors will be similar to control from conventional boilers burning low-sulfur coal.

Data from operating fluidized-bed

FBC process variations

Several variations of the FBC coal combustion process are under study. Primary features include:

- Pressure in the combustor. High pressures are employed when there is an incentive to generate electric power by expansion of high-pressure combustion off-gases through a gas turbine.
- Presence or absence of cooling surface in the bed. One concept envisions operation of the fluidized bed with no embedded heat-transfer surface, in order to maximize the energy content of combustion gases.
- Fluidization character—traditional dense-phase versus "fast", or "recirculating" fluidization. "Fast fluidization," which employs gas velocities higher than those used for dense-phase fluidization, but lower than those required for complete entrainment of the bed particles, is being studied by some investigators as a means for increasing coal throughput rate.
- Regeneration of the limestone sorbent that is used to control sulfur oxide emissions, to enable reuse of the sorbent, recovery of sulfur values, and reduction of the environmental impact of solids disposal.

FBC and current standards

The current NSPS for large coal-fired steam generators, larger than 250 million Btu/h, are:

SO_2	1.2 lb/10^6 Btu
NO_x	0.7 lb/10^6 Btu
Total particulates	0.1 lb/10^6 Btu

Revisions to those standards are entirely possible for the near future and one should not assume that large FBC boilers would be excluded from these revised standards.

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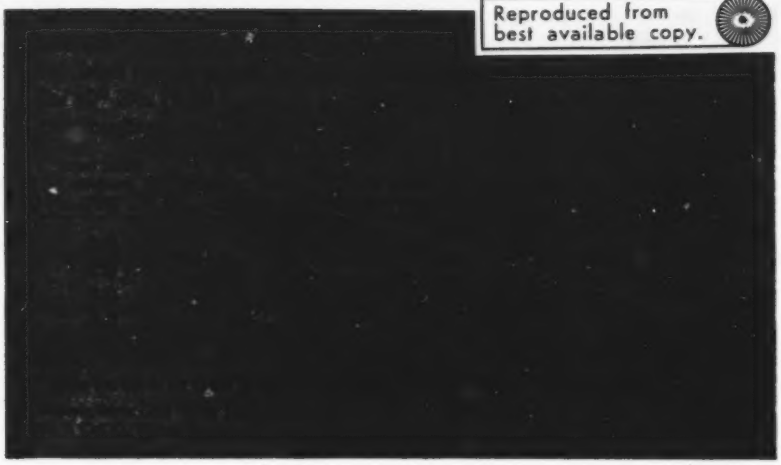

combustors employing cyclones indicate that, in order to meet the current emission standard, a final stage of particle control equipment will be necessary. It must be 80–97% efficient on particles with a mass mean size of about 7 μ.

The primary alternatives being considered to serve as the final particle-control device are electrostatic precipitators and baghouses. The performance of precipitators will be affected by the low SO_2/SO_3 levels expected in fluidized-bed combustor off-gases. Following in-situ particle resistivity measurements in the FBM, Pope, Evans and Robbins has concluded that a precipitator would probably have to be operated hot—650 °F or above—in order to achieve acceptable performance.

Among the final cleanup devices to be tested on large fluidized-bed boilers is a 750 °F precipitator at Rivesville. Baghouses will be tested on the 100 000 lb steam/h Georgetown University boiler, the 28 million-Btu/h Fluidyne/Owatonna Tool Co. heater, and the 6-MW atmospheric component test and integration unit being built by DOE at the Morgantown Energy Research Center.

Solid residue

Although firm conclusions cannot be drawn at this time regarding the acceptability of fluidized combustor residue, it is instructive to consider results obtained by Westinghouse from a substantial program of "shake" tests, in which small amounts of residue are shaken with water. The residue test included both spent bed material and carryover particulate from three atmospheric fluidized-bed combustors: the FBM at Pope, Evans and Robbins, a 3-foot by 3-foot unit at Babcock and Wilcox; and an 18-inch inner-diameter combustor operated by DOE's Morgantown Energy Research Center. The results of the testing on both the spent bed material and the carryover suggest that, at this stage, the following leachate characteristics do not appear to represent problems:

- total organic carbon (TOC)—leachate concentrations are below detection limits
- sulfide—leachate concentrations are below detection limits
- trace metals for which some type of drinking water or potable water standard, regulation or criterion exists, through EPA, the Public Health Service, or the World Health Organization (Ag, As, Ba, Be, Cd, Cr, Cu, Fe, Hg, Mn, Ni, Pb, Se, Sn and Zn)—leachate concentrations are below the drinking water standards.

It is emphasized that the above conclusions are tentative.

FBC has potential

Fluidized-bed combustion offers potential as a technique for utilizing coal as an energy source in the industrial use sector. Available data suggest that commercial atmospheric fluidized-bed combustion units should be technically capable of meeting the existing new source performance standards for SO_2 and NO_x emissions from large coal-fired steam generators. Achievement of the standard for particulates has not been demonstrated, but should be feasible through appropriate selection of particle control devices.

Data on large fluidized-bed combustion units are necessary. Limited data on solid waste from atmospheric fluidized-bed combustors presently suggest that the residue should not present disposal problems from the standpoint of sulfide, total organic carbon, and trace metals in the leachate. However, further consideration of the total dissolved solids, pH, calcium and sulfate composition of the leachate, and of heat release from the residue, is necessary in order to assure that no disposal problems exist with respect to these factors.

Additional reading

Farmer, M. H., Magee, E. M., Spooner, F. M., Application of Fluidized-Bed Technology to Industrial Boilers, prepared for FEA, ERDA and EPA by Exxon Research and Engineering Co., Report No. EPA-600/7-77-011 (January 1977) (NTIS No. PB 264-528/AS).

Proceedings of the Fluidized-Bed Combustion Technology Exchange Workshop, sponsored by the U.S. Energy Research and Development Administration (now DOE) and the Electric Power Research Institute, Reston, Virginia, April 13–15, 1977. Proceedings edited by the Mitre Corp./Meterek Division. (NTIS No. Conf-770447).

Pope, Evans and Robbins, Inc., Multicell Fluidized-Bed Boiler Design, Construction and Test Program, prepared for ERDA (now DOE), Research and Development Report No. 90, Interim Report No. 1 (August 1974).

Keairns, D. L., Archer, D. H., Hamm, J. R., et al., Fluidized-Bed Combustion Process Evaluation: Phase II—Pressurized Fluidized-Bed Combustion Development, (Appendices E, F, and G), prepared for EPA by Westinghouse Research Laboratories, Report No. EPA-650/2-75-027c (September 1975) (NTIS No. PB 246-116/AS).

Sun, C. C., Peterson, C. H., Newby, R. A., Vaux, W. G., Keairns, D. L., Disposal of Solid Residue from Fluidized-Bed Combustion: Engineering and Laboratory Studies, prepared for EPA by Westinghouse Research and Development Center, Report No. EPA-600/7-78-049 (March 1978).

Acknowledgments

The author wishes to acknowledge the assistance of D. L. Keairns, N. H. Ulerich, and C. C. Sun, all of Westinghouse Research and Development Center, and of K. S. Murthy of Battelle-Columbus Laboratories, in providing information for use in this article.

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